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Analysis of Complex 1 and Complex 2 Candidate Screening Models

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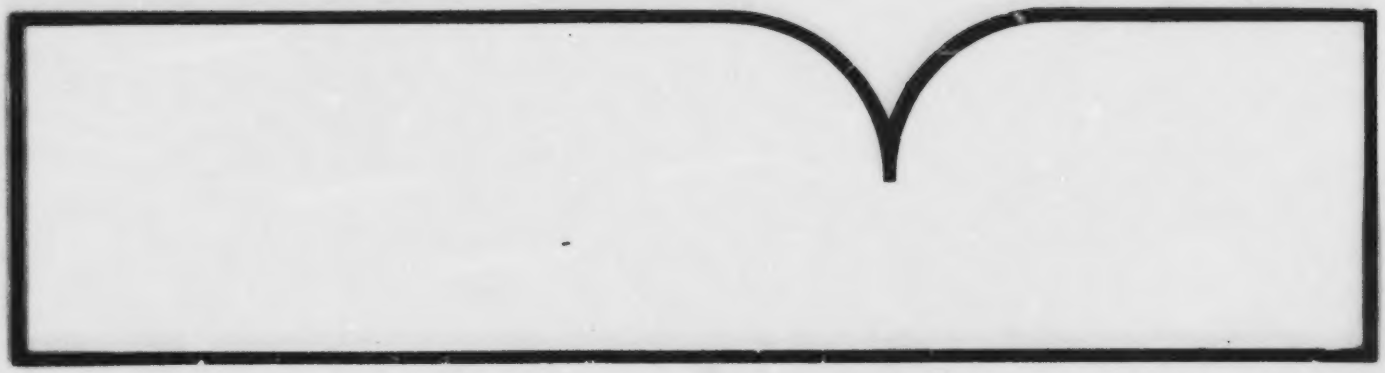

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AN ANALYSIS OF COMPLEX I AND COMPLEX II -- CANDIDATE SCREENING MODELS

by

John S. Irwin
D. Bruce Turner
Meteorology and Assessment Division
Environmental Sciences Reseach Laboratory
Research Triangle Park, North Carolina 27711

ENVIRONMENTAL SCIENCES RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
RESEARCH TRIANGLE PARK, NORTH CAROLINA 27711

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The models were applied and their results compared for a year's meteorological data for two different sites. Various combinations of source release height and terrain configurations were examined.

The authors conclude that the Valley-BID (or pencil and paper calculations using the same assumptions) are most appropriate for screening analyses for maximum 24-h concentrations resulting from plume impaction on terrain near the height of an elevated stabilized plume.

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AFFILIATION

Mr. Irwin and Mr. Turner are meteorologists in the Meteorology and Assessment Division, Environmental Sciences Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. They are on assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

FOREWORD

The Environmental Operations Branch in the Meteorology and Assessment Division of the Environmental Sciences Research Laboratory adapts and evaluates new and existing meteorological dispersion and statistical technique models, tailors effective models for recurring user application, and makes all models available through EPA's computer network system and on magnetic tape from the National Technical Information Service.

Complex II and Complex I are adaptations of the MPTER model and the Valley model as proposed by a workshop panel at an EPA Regional Workshop held in Chicago, February 25-28, 1980. The panel asked that a brief analysis be performed to investigate whether a sequential model, capable of accepting onsite hourly meteorological data could be recommended as a screening model for estimating worst-case pollutant impacts in complex terrain situations. This is a report of that brief analysis. Its scope and intent were limited by design, and it does not represent an assessment or position on complex terrain modeling.

A. H. Ellison

A. H. Ellison
Acting Director
Environmental Sciences Research Laboratory
Research Triangle Park, North Carolina

ABSTRACT

This study, suggested by an EPA Regional Workshop in February 1980, was conducted as a simple analysis to investigate whether or not a sequential air quality simulation model, capable of accepting onsite hourly meteorological data, could be recommended as a screening model for estimating worst-case pollutant impacts on complex terrain. The study intercompared the highest 24-h average pollutant concentration values obtained using four algorithmic air quality simulation models: Complex I, Complex II, Valley, and Valley-BID. Complex I and Complex II are sequential (hourly) air quality simulation models which differ only in their characterization of lateral dispersion. Complex I simulates lateral dispersion by assuming a uniform distribution of pollutant spread over a 22.5^{o} sector centered on the input hourly wind direction. Complex II simulates lateral dispersion by assuming a Gaussian distribution as specified by the input Pasquill stability category and the downstream distance. Valley is the standard EPA screening model used for estimating worst-case 24-h concentrations. Valley-BID is the Valley model, modified to incorporate the characterization of induced dispersion arising from buoyant plume rise into the vertical dispersion characterization.

The models were applied and their results compared for a year's meteorologial data for two different sites. Various combinations of source release height and terrain configurations were examined.

The authors conclude that the Valley-BID (or pencil and paper calculations using the same assumptions) are most appropriate for screening analyses for maximum 24-h concentrations resulting from plume impaction on terrain near the height of an elevated stabilized plume.

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SECTION 1

INTRODUCTION

This report presents the results of an analysis comparing the highest concentrations estimated for various averaging times by four air quality simulation models: Valley, Valley with buoyancy-induced dispersion (Valley-BID), Complex II, and Complex I. The analysis was suggested by the Complex Terrain panel of a regional workshop sponsored by EPA and held in Chicago, February 25-28, 1980. The panel outlined the characteristics of three of the models mentioned (Valley-BID, Complex II, and Complex I), which will be described later. The purpose of the sensitivity study was to see whether or not one of the two sequential (hourly) models, Complex II or Complex I, might provide a more detailed screening technique for use in complex terrain situations. (Complex terrain modeling applies whenever the terrain elevation is above the stack top of a point source.)

A more detailed screening model would allow a three-phase approach to the modeling of air quality in complex terrain. Phase 1 would be a simple screening procedure (most likely using Valley-BID) to determine whether or not the source clearly poses an air quality problem or if the potential for an air quality problem exists at all. If the simplified screening results indicate a potential threat to air quality, further analysis (Phase 2) would be warranted, using a detailed screening procedure. If these screening results in turn indicate that a yet more refined analysis is necessary, a refined model for complex terrain would be used as agreed upon with the Regional Office on a case-by-case basis (Phase 3).

Although no accepted model was available then for a more detailed screening analysis, the panel wanted to make specific recommendations. thus, they proposed that two sequential models (Complex II and Complex I) be assembled and a sensitivity analysis be accomplished in order to examine these models' usefulness for Phase 3 screening. Whether or not either of the proposed candidate models would be ultimately selected as the refined screening model was impossible to predetermine. Nor was it possible to predetermine if the proposed sensitivity analysis would provide a sufficient basis for making general recommendations regarding the use or non-use of the proposed models in regulatory decision-making. However, the working panel thought that the more specific the recommendations, the more likely the recommended model assembly and sensitivity analysis would be performed.

After discussion during the Complex Terrain session, the panel concluded first that a data base was needed before a refined model could be developed. The Office of Research and Development within EPA is currently collecting a data base for use in developing this model. Secondly, the panel suggested that the Phase 2 analysis should consist of calculations made using one of the sequential models to estimate actual measured pollutant concentrations.

The standard VALLEY model currently characterizes the lateral bounds of dispersion using a 22 1/2° sector; it characterizes vertical dispersion using the Pasquill-Gifford dispersion curves. No changes were recommended with regard to lateral dispersion. However, the panel did recommend that the total vertical dispersion , σ_z, be modified such that:

$$\sigma_z^2 = \sigma_{z_{P-G}}^2 + (\Delta h/3.5)^2 \qquad \text{(Eq.1)}$$

where σ_z = the total vertical dispersion and is a function of downstream distance, stability category, and plume rise

$\sigma_{z_{P-G}}$ = the Pasquill-Gifford vertical dispersion due to ambient turbulence which is a function of downstream distance and stability category

Δh = the plume rise which varies as a function of downstream distance until final rise is attained

The resulting model is the VALLEY-BID.

The sequential model Complex I uses meteorological input as currently available for CRSTER. The model determines vertical dispersion as described for the Valley model. Lateral dispersion dimensions in this model are bound by a 22 1/2° sector. Plume rise is estimated using subroutine BEH072 or equivalent. For stable conditions, the plume remains at a constant level above mean sea level (as presently employed in CRSTER). During neutral and unstable conditions (i.e., Pasquill categories A, B, C, and D), the plume follows one-half of the terrain height variation. The plume is not allowed to approach any closer than 10 m to the ground.

Complex II is identical to Complex I except that the lateral dimensions are given by:

$$\sigma_y^2 = \sigma_{y_{P-G}}^2 + (\Delta h/3.5)^2 \qquad \text{(Eq. 2)}$$

where σ_y = the total lateral dispersion and is a function of stability, downstream distance, and plume rise

$\sigma_{y_{P-G}}$ = the lateral dispersion due to ambient turbulence and is a function of Pasquill stability category and downstream distance

In this second model, $\sigma_{y_{P-G}}$ and $\sigma_{z_{P-G}}$ are specified using the same Pasquill stability categories. In other words, "split sigmas" are <u>not</u> recommended.

For the analysis, the panel recommended that both sequential models be executed along with the modified Valley screening model (Valley-BID) in two terrain situations, a broad valley and a narrow valley. All three models should be executed for three stack heights in the two terrains using two yearly periods of meteorology, one with a relatively uniform directional distribution, and one with a skewed directional distribution.

The following section containing conclusions and recommendations, also summarizes the major comments and recommendations made by reviewers regarding the use or nonuse of the proposed models. Section 3 outlines the analysis used to generate the results presented in Section 4. Section 5 contains short discussions on technical issues that are important in assessing the reasons for the differences in the modeled concentrations. And Section 6 lists the major questions posed to the reviewers.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

The original reason for examining concentrations from Complex I and Complex II and comparing with Valley and Valley-BID was to choose one of the two sequential models as a second level (Phase 2) screening technique.

The algorithm used in Complex I resulted in concentrations less than those given by the algorithm used in Complex II. This result was expected because of the uniform horizontal spreading in Complex I and the narrrower more peaked Gaussian distribution for horizontal spreading in Complex II.

A second result of the study was that the values resulting from Complex I were approximately the same as those obtained from Valley-BID.

The computational aspects of this study were completed, a draft report written and circulated among the members of the previously mentioned workshop panel. Although the conclusions reached by the authors and panelists are not unanimous this section attempts to present opinions of both the authors and other panel members.

It is the opinion of the authors that sequential models are useful when the meteorological data entered to the model can be considered representative of the flow for the particular situation being simulated.

The sequential models currently available, such as RAM, MPTER and CRSTER, employ one wind-direction to describe the flow for each hour. It is assumed in modeling the transport that conditions are horizontally homogeneous and stationary during each hour. These assumptions are rarely met. It is

quite likely that the flow field is rarely horizontally homogeneous. Violations of the assumption of horizontal homogenety cause the model to improperly locate the plume relative to the underlying surface. If the surface is relatively flat, one can usually assume that the dispersion, relative to the plume centerline, is independent of the horizontal location of the plume centerline. In such circumstances, the modeled concentration values can still be accepted, recognizing that the modeled locations of the maximum impacts are likely in error. When the dispersion relative to the plume centerline is dependent upon the underlying terrain and when the dependency is a function of the stability stratification (which is quite likely in complex terrain situations), it is necessary to properly locate the plume each hour relative to the underlying surface in order to have confidence in the modeled concentration values.

For a terrain situation where there are gradual rises in elevation to heights in excess of the elevation of the stack top but do not extend to the general plume heights, a single wind system may give a fairly good indication of the flow.

However, for a situation of a deep valley with sides extending to elevations beyond the usual plume heights, the wind direction from a single wind system may give reasonable indications of the flow for upvalley and downvalley conditions but the occurrence of indicated wind direction across valley may poorly represent the flow.

There, of course, exist many topographic situations between these extremes where it may be desirable to apply a screening model and the representativeness of the meteorological data is very difficult to determine.

For situations where the representativeness of the single set of

meteorological conditions is in doubt, the authors recommend the use of Valley-BID for screening analysis for the 24-hour averaging time. The version of the model using 2.6 as the stable plume rise constant should be used for consistency with other modeling approaches. Table 8 shows that at the distances from sources where Valley has been shown to give reasonable estimates of concentration, Valley-BID gives nearly the same concentrations. The inclusion of buoyancy-induced dispersion for large buoyant sources has long been recognized as desirable. In most cases of modeling over flat terrain, the inclusion of buoyancy-induced dispersion makes little difference in the estimated maximum concentration. However, for nearby receptors in complex terrain the difference can be considerable. Primarily because it is good modeling practice (rather than existence of field data for the near field), the use of buoyancy-induced dispersion is justified.

The screening calculations may be made with the Valley model using the buoyancy-induced dispersion option or closely approximated by pencil and paper calculations where terrain at plume height is being simulated. Two of the five reviewers essentially agreed with the authors.

Although two of the five reviewers agree that measurements at one point in a valley configuration are not necessarily representative of trajectories of air motion in the vicinity, they recommended the use of a sequential model such as Complex I (discounting calms, see later in this section) as a more justifiable approach than decision-making with Valley-BID alone, because Complex I considers onsite meteorological data. They reasoned that the manner in which the model performs impact (within 10 m) whenever receptor elevations are above plume height, and the tendency for a wind system to sense some cross-valley flow could cause the model to overestimate concentrations sufficiently

that it could be used as a screening tool in spite of its modeling deficiencies. Additional conveniences seen for using one of the models for screening are that concentrations could be calculated for elevations of "middle terrain", i.e., above stack top but below plume level, and calculations can be made for 3-h periods as well as for 24-h periods.

One reviewer, although leaning toward the position stated in the above paragraph, felt the issue of calms possibly obscures the screening analysis sufficiently that it is impossible to decide defensibly on the use of one of these models as a screening tool.

SPECIAL ISSUES HIGHLIGHTED BY REVIEW

Most modelers are aware that the meteorological conditions used for calculation in Valley-BID are not to be taken literally, but are simply a numerical mechanism for obtaining a value representative of the second-highest 24-h maximum concentration. The analytical routine for the Valley model "was not proposed as a rigorous mathematical description of the physical circumstances which pertain to flow about a terrain feature" (Burt and Slater, 1977).

To disprove the Valley model characterization of the plume geometry does not eliminate the possible occurrence of plume impingement. Likewise, the meteorological scenario employed by the Valley model for screening analyses is not meant to represent the conditions that must occur in order for plume impingement to occur. To disprove this particular meteorological scenario does not eliminate the possible occurrence of plume impingement resulting in concentrations as high as those generated by the Valley screening analysis.

Physical characterization of atmospheric flow over complex terrain is not easily achieved because the measurements needed to describe the flow

adequately are extremely difficult to obtain. For instance, great difficulty is encountered in estimating trajectories of air flow from single point measurements -- a definite obstacle for the use of simple models having straight line flow with sequential meteorological input. In addition, the modeler must also determine whether or not impingement will occur. This might be accomplished by considering the height of the streamline separating flow over an obstacle from flow around the obstacle.

Calculations from models such as Complex I and Complex II may vary greatly depending on how atmospheric calms are treated. For this study, calms were treated consistent with other modeling practice, i.e., the meteorological preprocessor output was used directly as input to the models. Thus calms were assigned a wind speed of 1 m/s and assigned a direction sector the same as the previous hour and then randomized to a direction to the nearest degree within that 10^{o} sector. Thus a sequential series of calms will all be assigned the same 10^{o} sector. Since Complex II is more sensitive to directional persistence than Complex I, results of comparisons between these two models might be quite disparate if calms were treated in a different manner.

One possible solution suggested by one of the reviewers to this sensitivity problem would be to eliminate calculation for hours of calm, and instead to estimate 24-h concentrations as the arithmetic average of the concentrations resulting for the non-calm hours. If less than 18 h resulted, no 24-h concentration would be reported. Note that following the above suggestion (deleting data for some hours) adds significant bookkeeping problems to initially rather simple models.

In response to the suggestion that calms be eliminated and parts of the analyses then repeated, no plans have been made to accomplish such a reanalysis.

Although modeling for flat terrain is much less sensitive to the treatment of calms than complex terrain modeling is, sensitivity to calms was raised as an issue for flat terrain modeling in the public meetings on modeling in October 1980 and was also discussed in the proposed modeling guidelines in October 1980 (U.S. Environmental Protection Agency, 1980).

Several reviewers questioned the manner in which the receptor networks were set up (in all directions at the same distance). This set up was possibly so unrealistic as to invalidate the sensitivity analysis since receptors int he direction of the wind rose maxima were not situated further away. An attempt was made to examine this factor in the analysis under Special Topics. The effect was to reduce the concentrations no lower than 0.7 of estimated maxima.

SECTION 3

ANALYSIS PROCEDURES

MODEL FABRICATION

Complex II and Complex I are identical except for the way in which they model lateral dispersion. Many of their features, such as buoyancy-induced dispersion and the ability to change plume height as a function of terrain elevation and stability, were adapted from the well-documented MPTER model (Pierce and Turner, 1980); the MPTER source code was used as the foundation for the Complex II and Complex I models. In August 1980, executable versions of Complex II and I were made available on the EPA UNIVAC computer system. The Regional Offices were notified of the models' availability and were requested to test them. In November 1980, the Regional Offices observed that the models did not handle receptor locations above the mean sea level of the final effective plume height in the same manner as the EPA Valley model. The Valley model decreases linearly the concentrations estimated with increasing receptor elevation height (above the plume level) to zero at and over 400 m above the undisturbed plume centerline. Thus, in December 1980 Complex II and Complex I were reprogrammed with regard to the treatment of the plume centerline and the resulting surface concentrations due to the terrain interaction with the plume.

The Valley model was modified to allow certain options, including the use of buoyancy-induced dispersion in the vertical dispersion parameter, and the use of the constant of proportionality, 2.4 or 2.6, for estimating

the final plume rise during stable conditions. The latter value of 2.6 reflects suggestions made by Briggs (1975). (Thus the Valley model available in UNAMAP, Version 4, is capable of simulating the models referred to in this document as Valley and Valley-BID.) A working copy of this modified version of Valley was further adjusted for the sensitivity study to allow the receptor locations to be input to the model in the same manner as the receptor locations are input to the Complex II and Complex I models. This made it easier to achieve congruency of receptors among the various models used in the sensitivity analysis.

In the following discussion, when reference is made to results generated using the Valley model, note that a constant of 2.6 was used for estimating final plume rise during stable conditions and no induced dispersion due to buoyant plume rise was included. Furthermore, the model was run as recommended to estimate worst case 24-h concentrations, i.e., Pasquill stability category F; 6 h of occurrence; and wind speed equal to 2.5 m/s.

When reference is made to Valley-BID, notice that the constant used in the stable plume rise is 2.6, the same meteorological conditions as with Valley are used and induced dispersion due to buoyancy is included in the vertical dispersion.

SOURCES

The workshop panel had suggested that the stack heights of the point sources used in the sensitivity analysis be 1/4 of the final effective plume height. Based on sources examined by Mills (1979), the researchers decided that the suggestion by the panel regarding the relationship between stack height and plume rise would not have been typical of most power and industrial plants. Using Mills (1979) the low, medium, and tall source characteristics were selected for the present evaluation and are presented in Table 1.

TABLE 1. POINT SOURCE CHARACTERISTICS

Source type	Stack height (m)	Stack diameter (m)	Exit velocity (m/s)	Exit temperature (K)	Emission rate (g/s)	Stable plume rise* (m)
Low	75	3	16	455	700	91
Medium	165	4	38	425	2,750	141
Tall	335	13	16	425	10,000	231

*Assumed wind speed of 2.5 m/s, vertical temperature gradient of 0.035 K/m, ambient temperature of 293 K.

The light wind stable plume rise estimates presented in Table 1 were made using the Briggs (1976) plume rise equations as used in Valley, Complex II, and Complex I. These plume rise estimates suggest that the ratio of stack height to final effective plume height during very stable conditions ranges from 0.45 to about 0.60.

VALLEY WALL PLACEMENT

Two valley configurations were used in the sensitivity analysis, a narrow valley and a broad valley. The narrow valley measured approximately 2 km in total width and the broad valley measured approximately 15 km. The intent was to investigate worst-case 24-hr concentration estimates at two downstream points. The narrow valley was used to study the effect on concentration estimates when buoyancy-induced dispersion was of primary concern. Two kilometers was chosen as the width of the narrow valley because the distance to final rise was generally just less than 1 km (assuming the source was in the center of the valley). The broad valley was used to study the effect on concentration estimates where buoyancy-induced dispersion was less important.

For the sensitivity analysis, two concentric cylindrical networks of receptors were placed around each pollutant source. The radii of the cylinders were 1 km and 5 km to simulate a narrow and a broad "valley". By using these receptor networks five different terrain configurations could be simulated in each run: flat terrain plus rising terrain at four different heights. (These networks were not to simulate a vertical canyon wall.)

A numerical processor was written that generated receptor locations for use as input to Complex II and Complex I. Initially, 180 receptors were generated at 10^{o} intervals and at 5 heights to form one of the cylinder walls. The heights were selected subjectively based on the stable plume rise for the source type. The maximum 24-h concentrations at each of the receptor locations were plotted as depicted in Figures 5 and 6, (presented later in Section 4). An objective analysis was not performed to determine the proximity of receptor spacing necessary to estimate the maximum 24-h average concentration to within some known percentage error at the given downwind distance. However, a subjective analysis was performed which consisted of searching for the maximum possible 24-h average concentration with receptors in 1^{o} intervals and 25 m vertical separation between receptors at the 1 km downwind distance.

The results for the low source suggest that the 24-h maximum concentration determined using the original receptor grid (10^{o} intervals with 25 m vertical spacing) was within 20% of the highest value determined during the analysis with 1^{o} receptor spacing. This result most likely represents an upper bound on the uncertainty of locating the maximum 24-h concentration since the low source had very strong gradients in the pattern of maximum 24-h concentrations. In any event, the 20% error was deemed tolerable for the purpose of judging variations in maximum concentrations between the models used in this study.

METEOROLOGICAL DATA

In seeking meteorological data for the sensitivity study, the intent was to see if skewness in the wind direction frequency caused by terrain channeling of the wind would affect the model results. Since the 1964 Knoxville, Tennessee, hourly surface meteorological data were readily available they were selected for use as the site having a skewed, bimodal wind rose, typical of sites in narrow valleys. The 1976 St. Louis surface meteorological data were selected as representative of a more circular wind rose site.

Figure 1 depicts the flow vector frequency relative to a completely circular wind frequency for the 1964 Knoxville data. If wind from every 10^{o} interval (from 10^{o} to 360^{o}) were as equally likely to occur, then 8784/36 = 244 hours would occur for each direction (note that 1964 and 1976 were both leap years). Therefore the flow vector frequency relative to a frequency equal from all directions was determined by dividing the number of hours of occurrence of each flow vector direction by 244. The hours of stable conditions and the hours of calm assigned by the preprocessor to each flow vector direction are also given in Figure 1. The hours of stable conditions follow fairly well the overall frequency distribution. Figure 2 depicts the same flow vector frequency for the 1976 St. Louis data.

A processor was constructed to convert the meteorological data into a format compatible for input to Complex II and Complex I. The processor set the mixing height to 5000 m; using a mixing height of 5000 m removes the mixing height as a variable affecting the concentration results due to reflection effects.

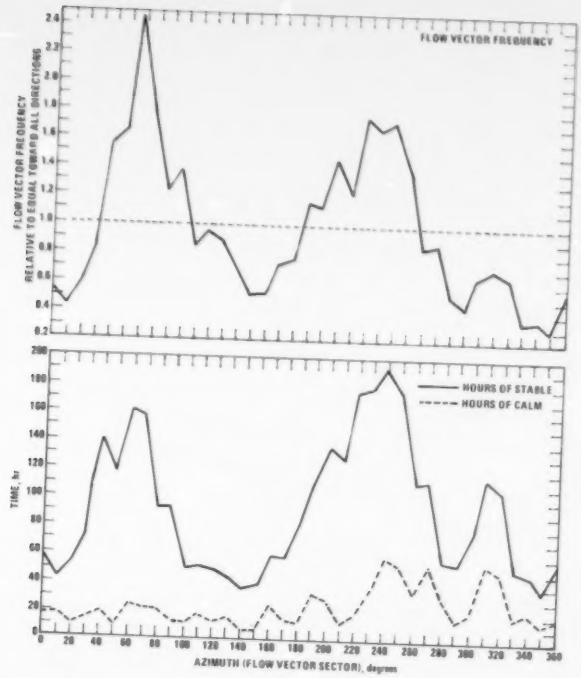

Figure 1. Flow vector frequency, hours of stable, and hours of calm, Knoxville, TN, 1964.

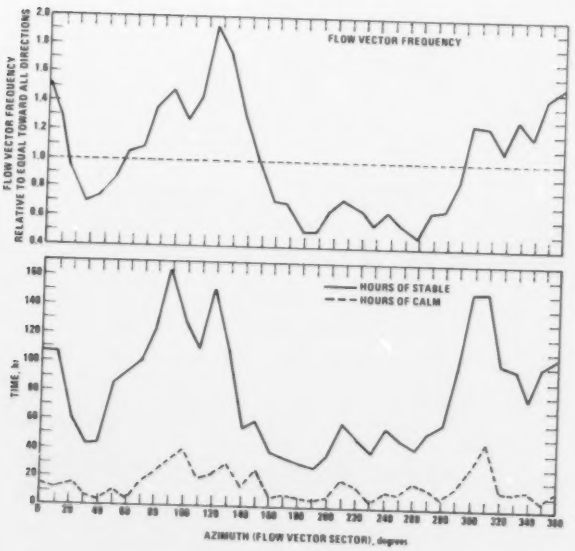

Figure 2. Flow vector frequency, hours of stable, and hours of calm, St. Louis, MO, 1976.

MODEL COMPUTATIONS ACCOMPLISHED

Twenty-four basic runs were made as part of the sensitivity study. The matrix showing the run numbers is shown in Table 2. Each of these runs was for a single pollutant source for 180 receptors, simulating a 1-yr period with output consisting of the high-five table. Nearly all runs were executed in a deferred batch mode of computer operation. This rendered costs to be 75% of those that would have been incurred under normal batch processing. Processing was generally done overnight. As many as 4 runs were executed per night so availability of computer facilities and turnaround were quite adequate for the study.

Execution of the runs required 56K of core or less. Each execution of COMPLEX II costs between $40 and $46. Each execution of COMPLEX I costs between $29 and $34. Each execution of Valley costs about $0.25.

TABLE 2. MATRIX OF RUN NUMBERS

Source	KNOXVILLE MET DATA				ST. LOUIS MET DATA			
	Complex II		Complex I		Complex II		Complex I	
	1 km	5 km	1 km	5 km	1 km	5 km	1 km	5 km
Low	1	2	7	8	13	14	19	20
Medium	3	4	9	10	15	16	21	22
High	5	6	11	12	17	18	23	24

Each run accessed 3 disk files and two disk file elements. Figure 3 is an example runstream. Since many of the runstreams were similar, the runstream itself was stored in a disk file element. This example was stored in WRKSHP.RUN6/XQT. The compiled and mapped model absolute for this run is in the element UNAMAP.COMPLEXIIABS. The hourly meteorological data for this example is in file FORKNOX64. The receptor list is in file GRHIGH1. For each run the output was placed into a print file, in this case PFRUN6., so that it could be edited if further computer processing of output became necessary.

```
@RUN, D/R 12ADR/70, ACCT NO., EOB, 23,50
@ . RUNSTREAM WRKSHP, RUN6/XQT
@SETC,O
@ASG, A UNAMAP.
@ASG, A GPHIGH1.
@ASG, A FORKNOX64.
@ASG, A PFRUNG.
@BRKPT PRINTS/PFRUNG
@XQT UNAMAP . COMPLEXIIABS
RUNS HIGH 1964 KNX/BNA 5 KM
IOPT(25)=1, BID, FINAL RISE, ZMIN=10, 1 DISTANCE, 5 HEIGHTS
INPUT BY A. RANKINS (ENVIRONMENTAL OPERATIONS BRANCH), 2/21/81
64, 1, 1, 366, 24, 3, 1, 0, 1., 1., 0.
1, 1, 1, 1, 1, 0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 1
10., .07, .07, .1, .15, .35, .55, .5, .5, .5, .5, .0, .0, 10.
HIGH STACK  0.    0.    10000.    0.    335.    425.    13.    16.
ENDP
@ADD GRHIGH1.
ENDREO
@ADD FORKNOX64.
@BRKPT PRINT$
@FREE PFRUN6
@SYM, U PFRUN6.,, FD04PR
@FIN
```

Figure 3. Example runstream.

SECTION 4

RESULTS

Plots were made initially to depict the variation of the maximum 24-h concentration at each downwind distance as a function of receptor elevation height and bearing from the source. Figures 4 and 5 are examples of such plots and are typical of the results in general. Several other examples of such plots are given in Appendix A. The maxima in these plots are quite localized, spanning 10 to 15° in horizontal azimuth and 100 m in the vertical. Tables 3 and 4 summarize the maximum 24-hour concentrations estimated using the Knoxville meteorological data. Figures 6, 7, and 8 depict these results with the Valley and Valley-BID estimates, for comparison. Table 5 lists the Valley and Valley-BID estimates.

TABLE 3. HIGHEST AND SECOND-HIGHEST 24-H CONCENTRATIONS RESULTING FROM COMPLEX II AND COMPLEX I AT 1 KM (KNOXVILLE, TN, 1964).

Source type	Receptor height (m)	Highest 24-hour concentration, $\mu g/m^3$		Second highest 24-hour concentration, $\mu g/m^3$	
		Complex II	Complex I	Complex II	Complex I
Low	200	11602.1	5145.4	7019.9	3759.6
	175	12157.6	5394.9	9018.3	3932.3
	150	11744.3	5251.0	8825.8	3920.4
	125	8935.4	2695.9	8252.0	2253.5
Medium	450	14708.9	6882.3	10440.8	5154.4
	350	20895.2	9761.8	14997.5	7331.7
	275	23066.8	10816.7	18174.3	8201.7
	200	2018.6	1083.5	1741.3	938.3
High	550	34997.4	18534.2	26518.9	13983.1
	525	36132.2	19084.6	28410.6	14212.4
	500	36929.2	19460.2	30077.9	14999.4
	475	32371.1	17194.0	26868.7	13537.3

TABLE 4. HIGHEST AND SECOND-HIGHEST 24-H CONCENTRATIONS RESULTING FROM COMPLEX II AND COMPLEX I AT 5 KM(KNOXVILLE, TN, 1964).

Source type	Receptor height (m)	Highest 24-hour concentration, $\mu g/m^3$		Second highest 24-hour concentration, $\mu g/m^3$	
		Complex II	Complex I	Complex II	Complex I
Low	200	1876.7	652.9	1270.0	508.3
	175	1977.8	744.8	1358.2	537.2
	150	1978.0	750.6	1400.0	555.8
	125	1454.8	557.3	1037.9	418.8
Medium	450	2845.0	1068.5	1860.4	773.3
	350	4019.0	1388.9	2671.1	1099.7
	275	4505.4	1711.9	3234.7	1237.4
	200	1180.9	474.1	877.2	389.7
High	550	8468.5	3202.4	5786.6	2369.4
	525	8710.6	3321.6	6198.8	2434.9
	500	8852.1	3406.6	6561.0	2516.1
	475	8005.2	3113.9	6052.9	2359.3

TABLE 5. VALLEY AND VALLEY-BID ESTIMATES OF MAXIMUM 24-H CONCENTRATIONS ($\mu g/m^3$).

Source	Valley		Valley-BID	
	1 km	5 km	1 km	5 km
Low	7,805	743	4,426	607
Medium	31,304	2,982	12,582	2,011
Tall	112,170	10,685	28,772	5,187

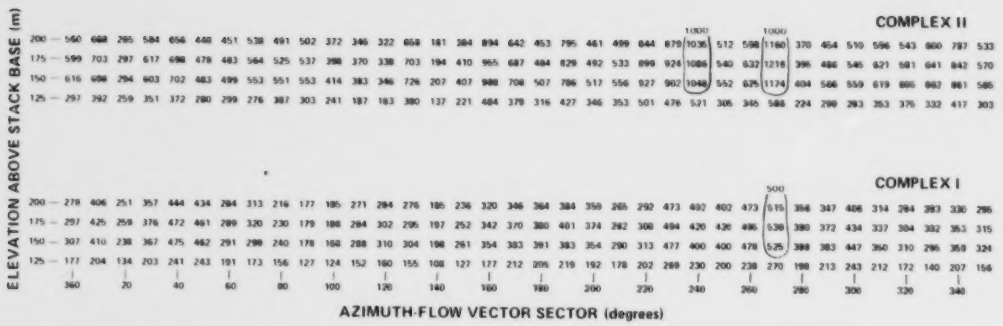

Figure 4. Maximum 24-h concentrations resulting from Complex II and Complex I at 1 km for the low source (Knoxville, TN, 1964). (Concentrations are $\mu g/m^3$ divided by 10).

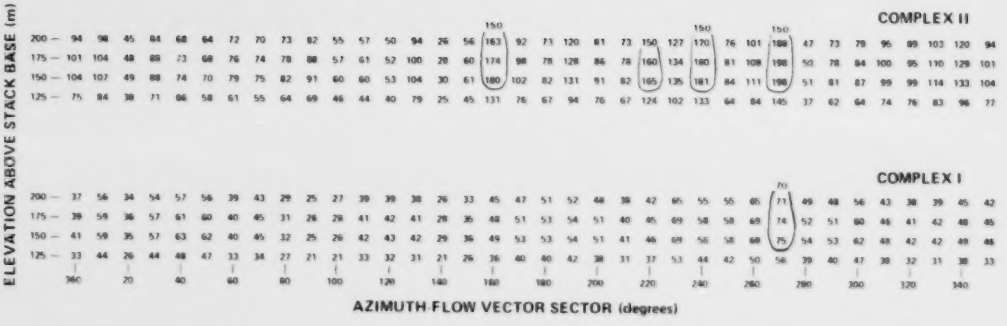

Figure 5. Maximum 24-h concentrations resulting from Complex II and Complex I at 5 km for the low source (Knoxville, TN, 1964). (Concentrations are $\mu g/m^3$ divided by 10).

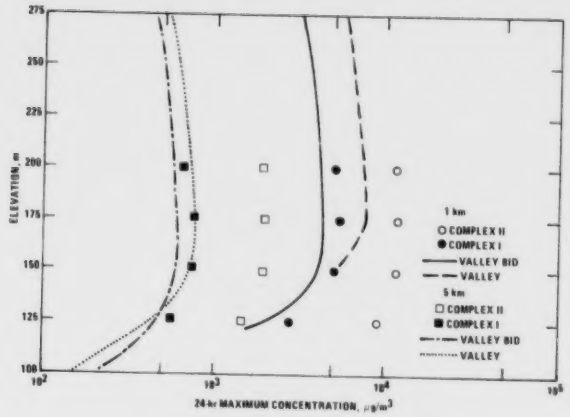

Figure 6. Comparison of 24-hr maximum concentrations as a function of height for the low source.

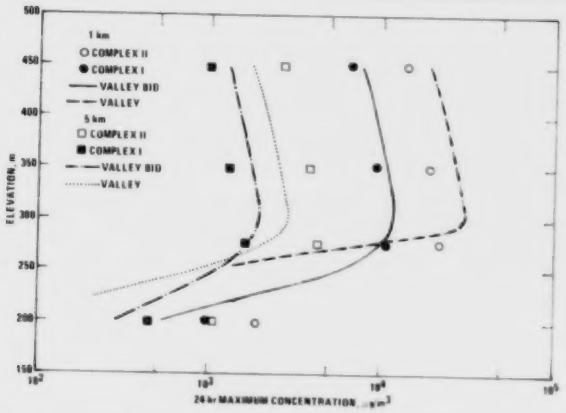

Figure 7. Comparison of 24-hr maximum concentrations as a function of height for the medium source.

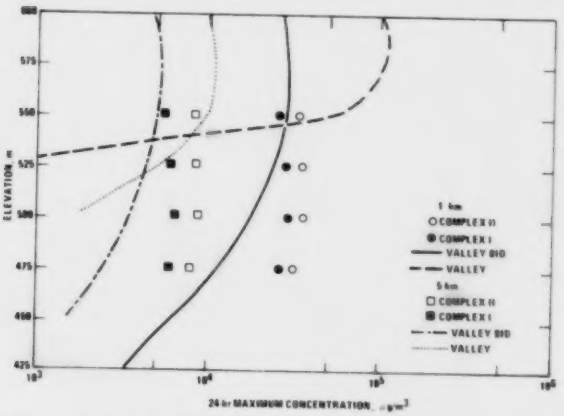

Figure 8. Comparison of 24-hr maximum concentrations as a function of height for the high source.

How calm conditions were modeled was the determining factor in the results just presented. The meteorological input data used for Complex II and Complex I were generated by a meteorological preprocessor. The processor performs the following functions: (1) calculates Pasquill stability class from cloud cover, ceiling height, wind speed, time of day, and time of year; (2) converts reported wind direction (in 10^{o} increments) to a flow vector (wind direction $\pm$ 180^{o}); (3) converts wind speed to m/s and converts air temperature to Kelvin; (4) generates a randomized flow vector from the above flow vector by using random digits to add from -4 to +5 to the flow vector to create random flow vectors to 1^{o} within the same 10^{o} sector; and 5) interpolates twice daily mixing heights to result in hourly estimates of mixing height. (Note that mixing height was effectively eliminated as a variable in this sensitivity study.) Note also that the treatment of winds reported as calm on the input is as follows: the speed is assigned 1 m/s, and the flow vector remains the same as for the previous hour. Thus, if a sequence of hours is reported as calm in the input data to the processor, although the randomized flow vector is varied over 10^{o}, the winds for this period are all at 1 m/s and are blowing toward only one 10^{o} sector. The developers of the preprocessor thought this procedure was the most reasonable one to handle calms since any topographic relief at a site might cause drainage flows with little direction change at nighttime when calms are most prevalent.

For the Complex II model, day 299 of the Knoxville data and days 238 and 320 of the St. Louis data caused the highest estimates of 24-h concentration. For the Complex I model, Julian day 299 of the Knoxville data and Julian day 320 of the St. Louis data caused the highest estimates of 24-h.

concentration for all three sources at both distances. Day 299 had 7 h of stable, calm conditions in which the wind directions were assigned by the preprocessor within the same 10° sector. Of these 7 h, 6 h were stability F or G and 1 h was stability E. Day 320 had 7 h of stable, calm conditions in which the assigned wind directions were within the same 10° sector. Of these 7 h, 6 h were stability F or G and 1 h was stability E. Day 238 had 6 h of stable, calm conditions, of which 5 h were F or G and 1 h was E. The wind speed at 10 m during these stable, calm conditions was assigned 1.0 m/s, since the meteorological preprocessor sets the wind speed to 1 m/s whenever a calm is reported. Complex II and Complex I extrapolate the 10 m wind speed to stack top height for use in the plume rise estimates and for use in the dispersion calculations. Differences between these extrapolated wind speeds and the 2.5 m/s speed assumed by Valley and Valley-BID account for most of the differences in maximum 24-h concentrations by Complex II and Complex I as compared with those generated using Valley and Valley-BID.

Table 6 attempts to summarize the variation in maximum concentrations one would anticipate given the four models used in this analysis. Column (6) of Table 6 lists the wind speeds at stack top that would be employed by Complex II and Complex I for calm, stability category F conditions. The differences in plume rise estimates (comparing the Valley and Valley-BID values to the Complex II and Complex I values), reflect the effects of differences in wind speed. Note, an ambient air temperature of 293 K was used for the plume rise estimates. Inspection of column (4) of Table 6 reveals that by using a higher wind speed in Complex II and Complex I, the vertical dispersion actually becomes less than that used in Valley-BID, because the buoyancy induced dispersion is proportional to the plume rise.

TABLE 6. DISPERSION AND WIND SPEED EFFECTS UPON MODEL ESTIMATES.

(1) Model type	(2) Source type	(3) X (km)	(4) Vertical dispersion (m)	(5) Lateral dispersion (m)	(6) Stack top wind speed (m/s)	(7) Stable-F plume rise (m)	(8) $\frac{\chi \text{ max (Expected)}}{\chi \text{ max (Valley-BID)}}$	(9) $\frac{\chi \text{ max (Calc.)}}{\chi \text{ max (Valley-BID)}}$
			*	†			‡	
Valley	Low	1	13.38	156.66	2.5	91	1.76	1.76
		5	35.71	783.32	2.5	91	1.22	1.22
	Medium	1	13.38	156.66	2.5	141	2.46	2.49
		5	35.71	783.32	2.5	141	1.47	1.48
	Tall	1	13.38	156.66	2.5	231	3.85	3.90
		5	35.71	783.32	2.5	231	2.04	2.06
Valley-BID	Low	1	29.24	156.66	2.5	91	1.00	1.00
		5	44.17	783.32	2.5	91	1.00	1.00
	Medium	1	42.45	156.66	2.5	141	1.00	1.00
		5	53.84	783.32	2.5	141	1.00	1.00
	Tall	1	67.34	156.66	2.5	231	1.00	1.00
		5	75.04	783.32	2.5	231	1.00	1.00
Complex I	Low	1	28.26	156.66	3.0	86	.86	1.22
		5	42.12	783.32	3.0	86	.87	1.24
	Medium	1	35.43	156.66	4.7	114	.63	.86
		5	47.23	783.32	4.7	114	.60	.85
	Tall	1	48.89	156.66	6.9	164	.50	.68
		5	58.01	783.32	6.9	164	.47	.66
Complex II	Low	1	28.26	41.86	3.0	86	3.22	2.75
		5	42.12	147.73	3.0	86	4.62	3.26
	Medium	1	35.43	47.00	4.7	114	2.09	1.83
		5	47.23	149.27	4.7	114	3.17	2.24
	Tall	1	48.89	57.83	6.9	164	1.34	1.28
		5	58.01	153.02	6.9	164	2.38	1.71

* Valley and Valley-BID compute σ_z differently than Complex I and Complex II because different algorithms are used to approximate the Pasquill dispersion curves. At 1 and 5 km the algorithms estimate the vertical dispersion parameter as:

X(km)	Valley Valley-BID	Complex I Complex II
1	13.38	13.95
5	35.71	33.88

† The lateral dispersion given is the effective σ_y for a sector model, computed as $(_1\sqrt{2\pi}/16)$ X, which was found by equating Eq. 5.13 and Eq. 3.3 of WADE (Turner, 1970) and solving for σ_y.

‡ List the ratio of the expected maximum 24-hour concentration to the Valley-BID estimate, for the given source type. Assumes a 4 to 1 relationship between the peak 1-hour and average 4-hour concentrations. Ratio is computed as:

$$\frac{\chi_{max} \text{ (Expected)}}{\chi_{max} \text{ (Valley-BID)}} = \frac{1/(\sigma_z \sigma_y u) \exp(-0.5(10\text{ m}/\sigma_z)^2)}{1/(\sigma_z' \sigma_y' u) \exp(-0.5(10\text{ m}/\sigma_z')^2)}$$

where primed quantities are values appropriate for Valley-BID calculations.

Decreasing the vertical dispersion tends to increase the maximum concentrations estimated to occur during plume impaction, while a higher wind speed tends to further dilute the pollutant and thereby lower the estimates. Column (8) of Table 6 lists the expected maximum 24-h concentrations (as compared to the corresponding results from Valley-BID for the given source type) as a function of pollutant source type and dispersion model. The assumption made in computing these ratios was that the peak 1-h concentration is four times the maximum 24-h concentration. In other words, the worst-case condition occurs for 6 out of 24 h. This assumption is the same one used in the short-term options of Valley and Valley-BID for estimating the maximum 24-h concentration. Column (9) of Table 6 lists the actual results (simulating 1 yr with the models) corresponding to those listed in column (8).

The differences in the results listed in columns (8) and (9) for the Valley model reveal that the actual maxima were not sampled by the vertical array of receptors used in the model runs. However, the differences suggest that the Valley and Valley-BID results are within 2% of the actual maximum values possible if one would happen to place a receptor directly on the maximum. The results listed for Complex I are a bit higher than would be anticipated. The primary cause for the differences is that the worst-case condition occurred for more than 6 h (usually 7 to 8 h with the inclusion of the hours with calms) during the 24-h period, and the 24-h concentration was thus slightly greater. Differences in plume rise caused by using air temperatures other than 293 K account for most of the other variations from the expected results. Since Complex II has a narrower lateral plume than that employed in Complex I, it is difficult to achieve the expected result that during 6 out of the 24 h the pollutant should reach the receptor.

This usually only occurs to within 1^{o} of the receptor for the 3 to 4 h, but never for 6 h. Reducing the frequency of the worst-case condition from 6 to 4 h accounts for most of the variation from the expected results listed for Complex II.

Appendix B lists the highest and second-highest concentrations estimated by Complex II and Complex I for the 3-h and 24-h averaging times. Also, tables are given for the medium source for the 5 highest ranked concentrations for various averaging times.

These results are in accord with the results discussed here in that the differences in handling the wind speed and the differences in characterizing the vertical and lateral dispersion describe the results. Besides the variation caused by these differences, the persistence of the worst-case condition during the averaging time of interest is all that is needed to summarize the variations seen between the results by the four models.

SECTION 5

SPECIAL TOPICS

In formulating a position regarding the proposed screening techniques, limitations must be recognized both in the model physics and in the present understanding of the processes. Plume impingement on elevated terrain during stable conditions is a complex process. The process can be summarized as a set of questions:

- Will the plume's trajectory reach the terrain?
- What are the minimum dimensions of the plume when it reaches and impinges on the terrain?
- What is the distribution of mass within the plume during impingement, relative to the surface of the terrain?
- If the concentration resulting during stable plume impingement were to result in worst-case (highest) 3-h and 24-h concentrations, what are reasonable values for the ratios of the worst-case 3-h and 24-h concentrations to the worst-case 1-h impingement concentrations?

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ALONG VERSUS CROSS VALLEY CONCENTRATION ESTIMATES

Since the sensitivity calculations were made as if terrain features existed at all possible azimuths from the source, it was desirable to examine what the effect would be upon the maximum concentrations if terrain features existed in only two of the possible four quadrants of 90° azimuth each.

The azimuth of highest flow vector frequency determined an axis referred to as "along" (see Figure 9). This is 60° for the 1964 Knoxville data and 120° for the 1976 St. Louis data. An axis at 90° to the along axis was referred to as "across." Quadrants were defined centered on these axes resulting in two along quadrants (A and B in Figure 9), and two across quadrants (C and D in Figure 9).

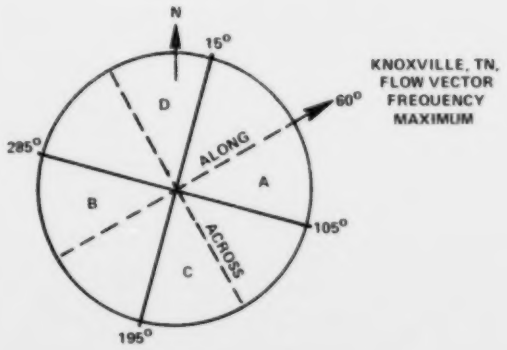

Figure 9. Quadrants oriented about the direction of maximum flow vector frequency.

A tabulation was then made of model estimates of 24-hour concentrations for the 24 computer runs by listing the maximum concentration in each of the four quadrants defined above.

The "along" quadrants were found to contain the highest 24-h concentrations for both the Knoxville and St. Louis data. However, these maxima were in quadrant B, which is opposite the quadrant of high flow vector frequency. (For the Knoxville data the direction of maximum flow vector frequency was 60°; the direction of the 24-h maximum concentration was 270°. For the St. Louis data the direction of maximum flow vector frequency was 120°; the direction of the 24-h maximum concentration was 310°.)

To assess the magnitude of the concentration on the valley sides compared to maxima in all directions, for valley situations having the two selected wind distributions, the ratio of the across quadrant maximum to the overall maximum was determined corresponding to all 24 runs made with the models. Consider first the results from the model Complex II. For the Knoxville data, the three source sizes had concentration ratios at 1 km ranging from 0.76 to 0.82 and at 5 km from 0.90 to 0.91. For the St. Louis data, the three source sizes had concentration ratios at 1 km ranging from 0.80 to 0.83 and at 5 km from 0.84 to 0.86. Using Complex I, for the Knoxville data, the three source sizes had concentration ratios at 1 km ranging from 0.82 to 0.86 and at 5 km from 0.82 to 0.83. For the St. Louis data, the three source sizes had concentration ratios at 1 km ranging from 0.71 to 0.72 and at 5 km from 0.71 to 0.72.

Thus, if locations with these wind distributions had terrain in two directions instead of all four, and one assumes that straight line flow could occur as indicated by the wind vane (see caveats on this point elsewhere in this document), then estimated concentrations would be between 0.7 and 0.9 of those estimated by runs with terrain in all directions depending on distance and model used.

A "spin off" of the above analysis is the consideration of lowest maximum 24-h concentration among the 36 azimuths. The ratio of this lowest 24-h maximum concentration (once a year) to the highest 24-h maximum concentration varied from 0.15 to 0.22 for Complex II and from 0.27 to 0.36 for Complex I. Thus, for these wind distributions, the azimuth with the lowest 24-h maximum had a concentration more than 1/7 that of the extreme maximum.

MODELING OF PLUME TRAJECTORIES

The sequential models still contain the inherent weakness of modeling dispersion downstream as straight paths along the input wind direction for the hour. In complex terrain this assumption is questionable. Hence, whether plume impaction as modeled actually occurs is not known. Nor is it known whether or not if the impact were to occur, it would occur as simulated. One could argue that the characterization of the lateral dimensions as a pie-shaped 22 1/2^{o} sector is obviously wrong and could not be verified by actual plume observations. But then one could also argue that it is questionable whether a plume can maintain a Gaussian cross-section both vertically and laterally while interacting with a sheer cliff or a steep bluff.

Because of these arguments, and similar ones not presented, caution must be exercised in formulating a recommendation for the use or nonuse of the proposed models. These models were not proposed because they were considered technically defensible; they were proposed because it was hypothesized that they would yield conservative estimates of the worst-case impacts in complex terrain.

The question which now must be addressed is whether or not models employing straight line-of-sight transport can successfully indicate the duration of and the nonoccurrence or the occurrence of plume impaction. Note that even a better representation of the plume's path in the vertical does not resolve the issue. The algorithms employed to estimate actual concentrations merely attempt to estimate the size of the plume and the distribution of the mass in relation to the receptor. The real issue is whether or not a model capable of only straight path transport can estimate the frequency (and the duration when it occurs) of material reaching each modeled receptor location?

This issue will not be solved any time soon. But it is important to realize that improper characterization of plume transport in the vicinity of major terrain features may lead to underestimates of maximum concentrations as well as overestimates. Consider the problem of an isolated point source in a narrow valley. The air flow within the valley is primarily constrained to be along the valley, but transport will also reflect the cross valley component of the flow. Hence the plume might "lay-up" along one valley wall and remain there persistently despite the fact that a single point measure of wind direction at the stack might indicate considerable wind direction variation.

Hewson and Gill (1944) discussed the meteorological processes affecting SO_2 transport within a portion of the Columbia River Valley near Trail, B.C. Here are some of their conclusions.

(Pg. 23)

> The effect of this irregular topography is to produce both large and small eddies. When the wind velocity is high, these eddies can be studied and largely accounted for. However, when the winds are very light, it is almost impossible to explain

> the variations in wind directions. Frequently, during periods of light winds, the smoke leaving each of the several stacks at the smelter can be observed going in a direction different from that taken by the smoke leaving the others. For instance the smoke leaving the Dwight-Lloyd stack may be moving up river and that from the zinc-plant stack going down river, while the smoke from the blast-furnace stack may be moving across the valley.
>
> (pg. 24,25)
>
> There are two general types of fumigations, diurnal and nondiurnal. The diurnal fumigations occur chiefly during the growing season. They are found at two periods of the day - from 08 to 10 hr. and from 18 to 20 hr. The nondiurnal fumigations show few clearly defined characteristics. Usually their strength is approximately inversely proportional to the distance from the smelter. ....Fumigations of this type may last several hours, or under stagnant winter conditions they may persist continuously for several days.
>
> (in discussing the diurnal fumigation pg 116)
>
> ... The concentration of sulfur dioxide on the west side of the valley at about 100 dkm is the interesting feature of this diagram. This location agrees very well with that anticipated from study of the east-west wind components at 05 hr., shown in figure 48. From this curve it can be seen that the sulfur dioxide will be kept on the west side of the valley by the strong components of wind from the east in the gas-carrying layer.

Hewson and Gill were summarizing an extensive field program complete with pibal wind observation, temperature soundings using kites and balloons, aircraft sampling, and surface monitors (most of which were on the Valley floor). Considerable effort was involved, largely due to the complex and often confusing transport that can result in the vicinity of major terrain features. A single wind instrument coupled with a simple line-of-sight transport model would not have explained or predicted the observed transport during the worst-case calm conditions.

Each complex terrain situation is most likely unique when viewed in detail. Broadly speaking, similarities may be found with other terrain

situations, however, it is impossible to quantitatively estimate the importance the details of the situation have on influencing the actual transport. What can be said is that simple models such as Valley, Valley-BID, Complex II, and Complex I, can characterize the size the plume might have if it were, by some process, to have reached each modeled receptor location. Considering the crude approach used to model the transport, it is impossible to determine whether or not a plume will affect a particular piece of real estate. In other words, models such as Valley, Valley-BID, Complex II, and Complex I may be able to tell something about the worst-case impacts one might expect at any given downwind distance, but, since these models can not model changes in transport due to complex terrain, they can not address whether or not the impact will occur.

EVALUATION OF VALLEY (1977)

The Valley model's performance was originally reported by Burt and Slater (1977). Their analysis consisted of a comparison of the Valley model estimates of second-highest 24-h concentrations with actual monitoring data. These monitoring data were the only such data available from sites on elevated terrain near "singular" polluting facilities. Burt and Slater's initial hypothesis (1970-1972) was that plume impingement during stable conditions, as simulated in the Valley Model, might well approximate the potential second-highest 24-h concentration annually; only later did field data become available.

The source data for that study are given in Table 7, and the model estimates and monitoring results are given in Table 8.

TABLE 7. SOURCE CHARACTERISTICS.

Site name	Source name	Stack height (m)	Plume * rise (m)	Emission rate (g/s)	Distance to receptor (km)	Plume height ‡ above receptor (m)	$(T/P)(P_o/T_o)$ ‡
Crusher	Garfield	124	160	3324	6.4	+71	1.1145
		124	140	2072	6.7	+20	
		29	49	202	7.0	-196	
		32	64	134	7.0	-178	
		15	15	2222	7.0	-244	
Lower-Lake Point	Garfield	124	160	3324	4.5	+74	1.1550
		124	140	2072	4.5	+23	
		29	49	202	4.5	-193	
		32	64	134	4.5	-175	
		15	15	2222	4.5	-241	
#106	Navajo Gen. Stn., Arizona	236	205	523	22.8	-97	1.1550
#107	Navajo Gen. Stn., Arizona	236	203	465	23.2	-169	1.2220
Phelps Mine	Morenci Smelter, Arizona	183	111	5522	4.7	-41	1.1282
		183	121	8060	4.7	-31	
Jones Ranch	Miami Smelter, Arizona	84	96	815	2.9	+43	1.1086
		61	83	3105	2.9	+7	

* For stability F, with 2.5 m/s wind speed at stack top; 2.4 constant used in plume rise formula.

† Negative indicates undisturbed stable plume final effective height is estimated to be below receptor elevation height.

‡ T is station temperature (K) and P is station pressure (mb). T_o and P_o are standard temperature and pressure, 298 K and 1013.2 mb respectively. Used to convert model estimates to STP or ppm.

TABLE 8. OBSERVED AND MODELED SO_2 CONCENTRATIONS.

Site name	Valley † (2.4)	Valley (2.6)	Valley-BID	Complex I	Complex II	Observed maximum 24-h Highest	Second highest	Period
Crusher	2480‡	2014	2199	3527	10966	2564	2473	$^4/_{73}$, $^1/_{74}$
						6130	3130	$^2/_{74}$, $^1/_{75}$
Lower-* Lake Point	1.18	0.94	1.08	1.88	5.57	2.66	1.20	$^3/_{75}$, $^{12}/_{75}$
						2.71	2.14	$^1/_{76}$, $^1/_{76}$
#106	36	38	27	22	77	32	19	$^{10}/_{74}$, $^2/_{75}$
#107	25	27	19	15	52	30	15	$^{10}/_{74}$, $^2/_{75}$
Phelps Mine	15490	15902	11006	8556	25438	2547	2416	1975
Jones Ranch	8610	7820	6357	8601	23998	2042	1760	1974
						2642	1548	1975

* Underscore indicates concentrations are reported in ppm, otherwise concentrations are reported in $\mu g/m^3$ reduced to STP.

† Valley (2.4) refers to the constant of 2.4 used to estimate the final plume rise during stable conditions. Likewise (2.6) refers to a constant of 2.6 being used in the stable plume rise estimates. Note, Valley-BID, Complex I, and Complex II use the 2.6 factor.

‡ As was done by Burt and Slater (1977), a 3 hour half life was assumed in all model estimates, and for receptors above the undisturbed plume centerline all the models reduced the concentration estimates by (401-Za)/400 where Za is the height (m) of the receptor above the centerline.

The results listed for Complex II and Complex I are actually results generated using the approximation formula outlined in Appendix C. The intent was to estimate the magnitude of plume impingement concentrations, not to estimate whether or not plume impingement would occur. This latter task was beyond the capabilities of any of the models employed in this analysis.

In looking at the differences in model estimates and observed concentrations, note that the emissions data are rough engineering estimates for all but the Navajo Generating Station.

It would seem all the models had difficulty for the Phelps Mine and Jones Ranch facilities. Perhaps plume impingement at the monitor sites never occurred or perhaps the emission rates were poorly characterized. The results indicate that Valley and Valley-BID performed better than Complex II and Complex I. As an aside, the Complex II results appear much better if all the estimates are divided by 2.0. This suggests that the overall dimensions of the plume may be well characterized by Complex II, but that the mass distribution is not quite appropriate. Complex II might provide useful results if reflection from 10 m below the centerline in the concentration algorithm were ignored.

WITHIN PLUME MASS DISTRIBUTION

Indoubtedly, the most controversial feature of the Valley model is the characterization of the mass distribution employed when plume impingement occurs. For receptor locations on terrain that extends above the modeled stable plume rise, the Valley model assumed that dispersion of material downward from the final effective plume height is inhibited. This assumption seems reasonable. However, controversy arises because impingement concentrations

are modeled by Valley as if the plume were restricted from dispersing any more than 10 m downward from the final effective plume height over the entire downstream transport. This effectively reduces the dispersion in the vertical to a rate 1/2 of that it would have if the plume were allowed to freely disperse downward (as it is allowed to disperse upward) during downstream transport. This causes concentrations to be two times higher than they otherwise would be.

It is important to realize that "effective" lateral dispersion, expressed as the ratio of centerline concentration of the sector-averaged Valley Model plume to that of the Gaussian plume (see Appendix C) ranges from just over 4.0 to almost 8.0 during F stability. Hence, the Valley model's maximum concentration estimates for receptors at plume elevation are from two to four times lower than would be estimated using no restriction to vertical dispersion and using the Pasquill F curve for the lateral dispersion.

EXTRAPOLATING TO LONGER AVERAGING TIMES

The extrapolation of short-term peak concentrations to the longer averaging times is at best a difficult process. The basic assumption in Valley is that in 6 h the entire plume has "swung across" a receptor; no assumption is made about the horizontal distribution of pollutant, except for mathematical convenience. Table 9 lists the peak to mean SO_2 concentration ratios observed during 1975 and 1976 at several monitoring networks operated by American Electric Power (AEP): Clifty Creek, Tanner Creek, Muskingum, and Gavin-Kyger-Sporn (Mills et al., 1980). These data would suggest that the 1:4 ratio is perhaps on the low side but within the observed range.

Table 9. PEAK TO MEAN RATIOS DURING PERIODS OF MAXIMUM 24-H CONCENTRATIONS

Receptor network	Year	Peak 1-h/24-h Concentration during Highest 24-h concentration	Peak 1-h/24-h Concentration during Second-highest 24-h concentration
Clifty Creek	1975	5.73	2.44
	1976	2.78	3.76
Tanners Creek	1975	1.69	1.62
	1976	2.39	3.70
Muskingum	1975	2.28	5.09
	1976	5.58	3.67
Gavin-Kyger-Sporn	1975	3.25	3.86
	1976	2.10	2.05

SECTION 6

QUESTIONS FOR REVIEWERS

The following questions were asked of the reviewers (Team B of the Chicago Workshop) of the first draft. Their replies to these questions are discussed in Section 2. Conclusions and Recommendations.

1. Based upon the summary information given in Figures 7 through 9, do you see any use for Complex II or Complex I as screening techniques?
2. Does the point that none of these models can be used for estimating concentrations and frequency of occurrence at a specific point come across clearly?
3. Do you agree or disagree with our recommendation on the labeling of the Valley-BID results as a screening model estimate valid <u>if</u> plume impingement occurs? NOTE: this implies that Valley-BID is not sensitive enough to judge whether or not impingement will occur, only that <u>if</u> impingement occurs then, thus and so may occur.
4. Does the analysis discussed in this draft include all the computations that you wanted in the sensitivity analysis?
5. Are there questions about sensitivity that you believe can be answered by the computations made that are either not stated here or that insufficient information from the computations are presented so that the reader can infer the appropriate answer?
6. Please give particular attention to review of the recommendations made in Section 2. On which point or points do you disagree? Are there additional points that should be included here?

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APPENDIX A

ADDITIONAL FIGURES OF MAXIMUM 24-H CONCENTRATIONS

Figures A-1 and A-2 are similar to Figures 5 and 6 but are the result of using the St. Louis meteorological data.

Figures A-3 gives maximum 24-h concentrations resulting from Complex II at 1 km for the medium and high sources using the Knoxville data.

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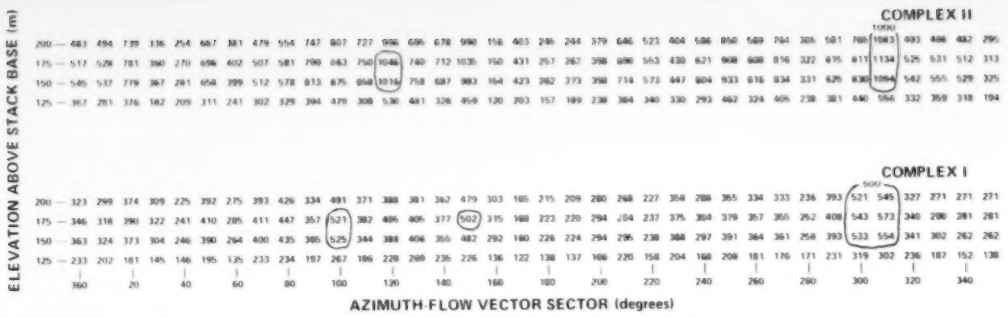

Figure A 1. Maximum 24 h concentrations resulting from Complex II and Complex I at 1 km for the low source (St. Louis, MO, 1976). (Concentrations are $\mu g/m^3$ divided by 10).

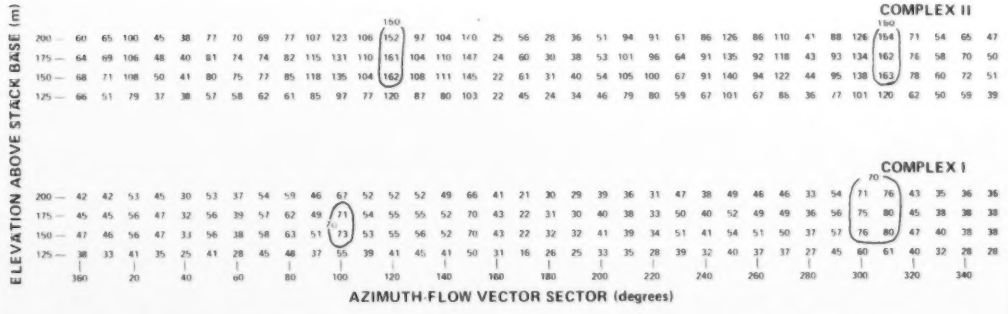

Figure A 2. Maximum 24 h concentrations resulting from Complex II and Complex I at 5 km for the low source (St. Louis, MO, 1976). (Concentrations are $\mu g/m^3$ divided by 10).

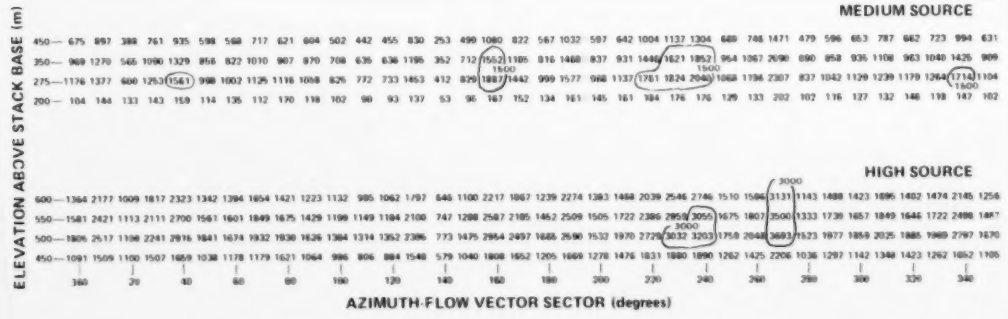

Figure A 3. Maximum 24 h concentrations resulting from Complex II at 1 km for the meduim and high sources using the Knoxville, TN, 1964 data. (Concentrations are $\mu g/m^3$ divided by 10).

APPENDIX B

HIGHEST AND SECOND HIGHEST CONCENTRATIONS

AND

CONCENTRATIONS FOR VARIOUS AVERAGING TIMES

Tables B-1 through B-4 give the highest and second highest concentrations estimated from the two models Complex II and Complex I for two averaging times, 24-h and 3-h. The azimuth of the receptor relative to the source,the elevation above the source stack base, the Julian day of the estimate,and the hour ending the period, if appropriate, are listed with each estimated concentration. Tables B-1 and B-2 are for Knoxville data; Figures B-3 and B-4 are St. Louis data. Tables B-1 and B-3 are for Complex II; Tables B-2 and B-4 are for Complex I.

Tables B-5 and B-6 give the five highest model estimates for four different averaging times. Tables B-5 is for Knoxville data; Table B-6 is for St. Louis data.

Using data from Table B-5 (Knoxville), the second highest from both models for each distance as a function of averaging time was graphed. This is displayed in Figure B-1.

The five highest concentrations using the Knoxville data (again from Table B-5) are displayed in Figure B-2 in rank order for the four averaging times for the two models, Complex II and Complex I.

TABLE B-1. HIGHEST AND SECOND-HIGHEST 3-H AND 24-H CONCENTRATIONS FROM COMPLEX II (KNOXVILLE, TN, 1964).

Source	1 km					5 km				
	Conc.	Azi.	Elev.	Day	Hour	Conc.	Azi.	Elev.	Day	Hour
Low										
24-hour										
High	12157	270°	175m.	299		1978	270°	150m.	299	
Second high	9018	270°	150m.	22		1400	270°	150m.	22	
3-hour										
High	51053	330°	150m.	249	3	8950	330°	150m.	249	3
Second high	45054	270°	150m.	299	6	7758	270°	150m.	299	6
Medium										
24-hour										
High	23067	270°	275m.	299		4505	270°	275m.	299	
Second high	18174	270°	275m.	22		3235	270°	275m.	22	
3-hour										
High	96704	330°	275m.	249	3	20306	330°	275m.	249	3
Second high	86935	270°	275m.	299	6	17633	270°	275m.	299	6
High										
24-hour										
High	36929	270°	500m.	299		8852	270°	500m.	299	
Second high	30078	270°	500m.	22		6561	270°	500m.	22	
3-hour										
High	147174	330°	500m.	249	3	40702	330°	500m.	249	3
Second high	132200	270°	500m.	22	3	34907	270°	500m.	299	6

TABLE B-2. HIGHEST AND SECOND-HIGHEST 3-H AND 24-H CONCENTRATIONS FROM COMPLEX I (KNOXVILLE, TN, 1964).

Source	1 km					5 km				
	Conc.	Azi.	Elev.	Day	Hour	Conc.	Azi.	Elev.	Day	Hour
Low										
24-hour										
High	5394	270°	175m.	299		751	270°	150m.	299	
Second high	3932	250°	175m.	309		556	240°	150m.	350	
3-hour										
High	15637	120°	150m.	207	3	2170	110°	150m.	207	3
Second high	15563	320°	150m.	245	3	2165	320°	150m.	245	3
Medium										
24-hour										
High	10817	270°	275m.	299		1712	270°	275m.	299	
Second high	8202	270°	275m.	22		1237	250°	275m.	309	
3-hour										
High	32444	120°	275m.	207	3	4953	110°	275m.	207	3
Second high	32341	320°	275m.	245	3	4943	320°	275m.	245	3
High										
24-hour										
High	19460	270°	500m.	299		3406	270°	500m.	299	
Second high	14999	270°	500m.	22		2516	270°	500m.	22	
3-hour										
High	58758	120°	500m.	207	3	9972	110°	500m.	207	3
Second high	58613	320°	500m.	245	3	9958	320°	500m.	245	3

TABLE B-3. HIGHEST AND SECOND-HIGHEST 3-H AND 24-H CONCENTRATIONS FROM COMPLEX II (ST. LOUIS, MO, 1976).

Source	1 km					5 km				
	Conc.	Azi.	Elev.	Day	Hour	Conc.	Azi.	Elev.	Day	Hour
Low										
24-hour										
High	11343	310°	175m.	238		1627	310°	150m.	238	
Second high	11163	310°	175m.	320		1541	310°	150m.	320	
3-hour										
High	51218	150°	150m.	305	24	9452	150°	150m.	305	24
Second high	43741	100°	150m.	302	3	7295	100°	150m.	302	3
Medium										
24-hour										
High	22476	310°	275m.	320		3772	310°	275m.	238	
Second high	22138	310°	275m.	238		3549	310°	275m.	320	
3-hour										
High	96631	150°	275m.	305	24	21442	150°	275m.	305	24
Second high	83855	100°	275m.	302	3	16563	100°	275m.	302	3
High										
24-hour										
High	37693	310°	500m.	320		7587	310°	500m.	238	
Second high	36559	310°	500m.	238		7161	310°	500m.	320	
3-hour										
High	145823	270°	500m.	262	3	42224	150°	500m.	305	24
Second high	128851	100°	500m.	302	3	32910	100°	500m.	302	3

TABLE B-4. HIGHEST AND SECOND-HIGHEST 3-H AND 24-H CONCENTRATIONS FROM COMPLEX I (ST. LOUIS, MO, 1976).

Source	1 km					5 km				
	Conc.	Azi.	Elev.	Day	Hour	Conc.	Azi.	Elev.	Day	Hour
Low										
24-hour										
High	5726	310°	175m.	320		801	310°	150m.	320	
Second high	5560	310°	175m.	232		775	310°	150m.	232	
3-hour										
High	15665	360°	150m.	235	24	2172	360°	150m.	235	24
Second high	15612	360°	150m.	236	3	2168	360°	150m.	236	3
Medium										
24-hour										
High	11689	310°	275m.	320		1831	310°	275m.	320	
Second high	11438	310°	275m.	232		1775	310°	275m.	232	
3-hour										
High	32482	360°	275m.	235	24	4955	360°	275m.	235	24
Second high	32410	360°	275m.	236	3	4949	360°	275m.	236	3
High										
24-hour										
High	21242	310°	500m.	320		3637	310°	500m.	320	
Second high	20672	310°	500m.	232		3536	310°	500m.	232	
3-hour										
High	58799	360°	500m.	235	24	9975	360°	500m.	235	24
Second high	58712	360°	500m.	236	3	9967	360°	500m.	236	3

TABLE B-5. FIVE HIGHEST MODEL ESTIMATES FOR 1-, 3-, 8-, AND 24-H AVERAGING TIMES (MEDIUM SOURCE; KNOXVILLE, TN, 1964).

Averaging time (H)		Complex II 1-km	Complex I 1-km	Complex II 5-km	Complex I 5-km
1-H					
Highest		109044.8	37717.7	26072.8	5406.9
Highest 2nd high	(a)	**108163.8**	**37638.0**	**25990.9**	**5406.6**
Highest 3rd high		107647.3	37563.3	25938.4	5406.2
Highest 4th high		107647.3	37560.2	25938.4	5405.7
Highest 5th high		106309.6	37549.3	25808.8	5405.3
3-H		96704.0	32444.2	20305.9	4952.6
		86935.4	32341.0	17633.2	4943.4
		76877.1	32120.9	14281.1	4923.6
		69812.1	32016.4	12807.7	4915.1
		58769.4	31677.9	12236.4	4884.3
8-H		69133.3	29447.4	13419.4	4614.8
		49693.0	22761.4	8920.0	3483.1
		39627.6	22279.2	6186.6	3386.6
		34317.6	20061.8	6175.1	3077.7
		31050.5	17997.1	6007.6	2666.2
24-H	(c)	**23066.8**	**10816.7**	**4505.4**	**1711.9**
	(b)	**18174.3**	**8201.7**	**3234.7**	**1237.4**
		14005.0	8157.8	2308.2	1231.5
		12486.0	7656.7	2259.0	1176.1
		11439.2	6979.2	2007.1	1093.8
(a)/(b)		5.95	4.59	8.04	4.37
(c)/(b)		1.27	1.32	1.39	1.38

(a) Second highest 1-H
(b) Second highest 24-H
(c) Highest 24-H

TABLE B-6. FIVE HIGHEST MODEL ESTIMATES FOR 1-, 3-, 8-, AND 24-H AVERAGING TIMES (MEDIUM SOURCE; ST. LOUIS, MO, 1976).

Averaging time (H)		Complex II 1-km	Complex I 1-km	Complex II 5-km	Complex I 5-km
1-H					
Highest		109189.6	37852.9	26084.9	5406.1
Highest 2nd high	(a)	**107851.2**	**37661.3**	**25958.0**	**5405.5**
Highest 3rd high		107145.6	37606.6	25890.0	5404.5
Highest 4th high		106852.9	37597.1	25861.6	5404.2
Highest 5th high		100405.2	37565.4	21845.0	5404.2
3-H		96690.5	32482.3	21442.4	4955.5
		83855.0	32409.6	16563.0	4949.0
		77658.3	32308.3	13485.0	4940.1
		66292.6	32259.7	11617.2	4935.7
		65192.6	31760.0	10889.8	4935.2
8-H		61749.3	30459.5	11103.0	4795.3
		60951.1	26259.1	9750.1	3969.6
		43777.2	24060.8	6845.9	3733.9
		43707.9	20882.4	5860.9	3173.0
		41404.2	20713.6	5042.4	3085.6
24-H	(c)	**22475.9**	**11688.7**	**3771.7**	**1831.3**
	(b)	**22137.5**	**11437.8**	**3549.3**	**1774.6**
		16052.3	10637.4	2525.6	1645.8
		15519.6	8112.0	2275.9	1254.3
		14592.4	7987.3	1778.8	1205.1
(a)/(b)		4.87	3.29	7.31	3.05
(c)/(b)		1.02	1.02	1.06	1.03

(a) Second highest 1-H
(b) Second highest 24-H
(c) Highest 24-H

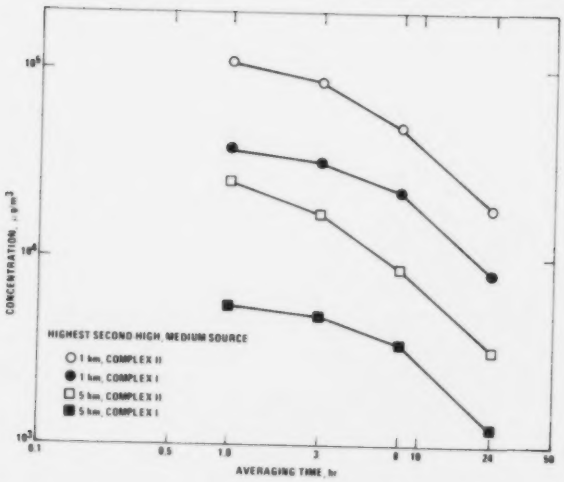

Figure B.1. Highest second high concentrations as a function of averaging time from Knoxville, TN, 1964 data.

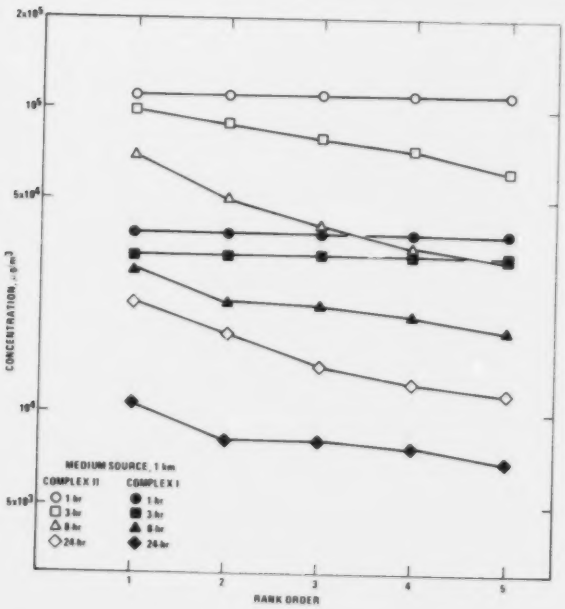

Figure B.2. Five highest estimated concentrations in rank order for 1-, 3-, 8-, and 24-hr averaging times from Complex II and Complex I using Knoxville, TN, 1964 data.

APPENDIX C

MODEL ESTIMATES BY HAND CALCULATIONS

The results from the Valley and Valley-BID models, when executed in their screening mode, for estimating worst-case 24-h concentrations can be duplicated rather simply using a calculator. The procedure for duplicating the Valley and Valley-BID results can also be made to approximate the results from Complex II and Complex I, generated in this sensitivity analysis. The computations of plume rise, vertical dispersion, and lateral dispersion need be computed only once per downwind distance. Then equation (C-1) can be used to approximate the various models. Equation (C-1) will tend to overestimate the maximum concentrations for 3-, 8-, and 24-h averaging times from Complex II and Complex I as downwind distance increases beyond 5 km. However, it would not be that difficult to further investigate the variation of R as a function of downwind distance and thereby develop a simple tool for screening analyses in complex terrain situations.

The following discussion outlines the four-step procedure. The first step is to determine the wind speed which is a constant for Valley and Valley-BID and is a function of stack height for Complex II and Complex I. The second step is to compute the stable plume rise. The third step is to compute the vertical and lateral dispersion for the downwind distance of interest, and the fourth step is to substitute the results into equation (C-1). The procedures lend themselves to programmable pocket calculators.

The factor R has been chosen to slightly overestimate the sequential model results for the 1- to 5-km downwind distance range. Generally, the results of Equation (C-1) are within 15% of actual modeled results for Complex II and Complex I. There is no error as far as Valley and Valley-BID is concerned, except for those minor differences introduced by the characterization used for the vertical dispersion during Pasquill F stability category. This particular characterization of σ_z is from Vogt[11].

If the receptor elevation is above the undisturbed height of the plume, the concentration resulting from equation (C-1) should be multiplied by (401-ZR)/400, where ZR is the height in meters of the receptor elevation above the undisturbed plume. For instance, say we had a stack height of 100 m, a plume rise of 150 m, and a receptor elevation above stack base of 275 m. In such a case, the receptor would be 25 m above the undisturbed final plume height and ZR would equal 25 m and H in equation (C-1) would equal 10 m.

1. Compute wind speed at stack top during 1-h period of assumed worst-case stable conditions.

   A. Valley or Valley-BID

      $u = 2.5$ m/s

   B. Complex II or Complex I

      $u = (h_s/10)^{0.55}$

      where h_s = stack height (m)

2. Compute stable plume rise

$$\Delta h = 5.007 \left[\frac{V_s d^2 T}{u T_s} (T_s - T) \right]^{1/3}$$

or

$$\Delta h = 5.427 \left[\frac{V_f T}{u T_s} (T_s - T) \right]^{1/3}$$

V_s = stack gas exit velocity (m/s)

d = stack exit diameter (m)

T = ambient air temperature, ~293 K

T_s = stack gas exit temperature (K)

u = assumed wind speed at stack top (m/s)

V_f = stack gas volume flow (m^3/s), equal to

$(\pi/4))V_s d^2$

3. Compute vertical and lateral dispersion

A. Valley

$$\sigma_{z_o} = \left(\frac{1}{2.15}\right) \exp(-3.8 + 1.419 \ln X - 0.055 \ln^2 X)$$

$$\sigma_{y_o} = (\sqrt{2\pi}/16)X$$

X = downwind distance (m)

B. Valley-BID or Complex I

$$\sigma_z = [\sigma_{z_o}^2 + (\Delta h/3.5)^2]^{1/2}$$

where σ_{z_o} is as given for Valley

σ_{y_o} = as given for Valley

Δh = stable plume rise (m)

C. Complex II

σ_z = as given for Valley-BID

$$\sigma_y = [\sigma_{y_o}^2 + (\Delta h/3.5)^2]^{1/2}$$

$$\sigma_{y_o} = (-0.0029 \ln X + 0.054)X$$

4. Compute concentration estimate

$$X = \frac{R\ Q\ 10^6}{\pi \sigma_z \sigma_y\ u} \exp\ -\frac{1}{2}\ \left(\frac{H}{\sigma_z}\right)^2 \qquad \text{(C-1)}$$

X = maximum concentration for averaging time ($\mu g/m^3$)

H = minimum separation between plume centerline and receptor, no less than 10 m.

Q = emission rate (g/s)

R = ratio of maximum concentration for averaging time of interest to 1-h peak.

	Averaging Time (h)		
	3	8	24
Valley or Valley-BID	Not applicable	Not applicable	0.25
Complex II Iopt(25)=1	0.90	0.60	0.20
Complex I Iopt(25)=1	0.95	0.85	0.35

REFERENCES -- APPENDIX C

Vogt, Kurt-Jurgen, 1977: Empirical investigations of the diffusion of waste air plumes in the atmosphere, Nuclear Technology 34, 43-57.